PROCEEDINGS OF SCIENCE

Search for rare decays

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In these proceedings, the recent measurements of the $B_s^0 \to \mu^+\mu^-$ decay branching fraction and its effective lifetime and the search for the $B^0 \to \mu^+\mu^-$ decay using the data collected by the CMS experiment at LHC between the years 2011 and 2016 have been presented. Recently, a combined analysis of the decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ by ATLAS, CMS, and LHCb has been performed, which is also discussed in this paper. The third part of these proceeding includes the search for τ leptons decaying into three muons using the data collected by the CMS experiment in 2016.

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1. Introduction

The rare decay of B_s^0 and B^0 mesons into a pair of muons are the most promising mode to search for an unseen physics effect. These leptonic decay modes are forbidden at tree level in the Standard Model (SM). Nevertheless, it can occur in the Z-penguin and box diagrams. In addition to being loop and CKM suppressed, decays are furthermore helicity suppressed by factors $m_l^2/m_{B_{(s)}^0}^2$ where m_l and $m_{B_{(s)}^0}$ denote the masses of leptons ($l = \mu, e$) and $B_{(s)}^0$ mesons. The branching fraction of $B_s^0 \to \mu^+\mu^-$, and $B^0 \to \mu^+\mu^-$ and effective lifetime of the B_s^0 meson in the $B_s^0 \to \mu^+\mu^-$ mode are the key observables. The first observation of the $B_s^0 \to \mu^+\mu^-$ decay was a combined analysis performed by CMS and LHCb [1]. Later, this decay has been studied to precisely measure the properties by ATLAS [2], CMS [3], and LHCb [4]. Since, then the $B^0 \to \mu^+\mu^-$ decay has not been observed yet, but many experiments perform the search with great enthusiasm. The effective lifetime is defined by

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\langle\Gamma(B_s^0(t) \to \mu\mu)\rangle dt}{\int_0^\infty \langle\Gamma(B_s^0(t) \to \mu\mu)\rangle dt} \equiv \frac{\tau_{B_s^0}}{1 - y_s^2}\left(\frac{1 + 2A_{\Delta\Gamma}y_s + y_s^2}{1 + A_{\Delta\Gamma}y_s}\right) \tag{1}$$

where, $A_{\Delta\Gamma}$ and y_s are defined by $-\mathscr{R}(\lambda)/(1 + |\lambda|^2)$ and $\tau_{B_s^0}\Delta\Gamma_s/2$, respectively. In the SM, only the heavy state decays to $\mu^+\mu^-$, but this condition does not necessarily hold in the case of physics beyond the SM. The SM predicts [5, 6] $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.57 \pm 0.17) \times 10^{-10}$, $\mathscr{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$ and $\tau_{\mu^+\mu^-} = 1.615$ ps. Details of the analysis are documented in Ref [3].

1.1 Event selection

The signal decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are reconstructed by taking the opposite charge muons emerging from the same displaced decay vertex. The directions of momentum and flight should align in the same direction, and the invariant mass should peak around the $M(B^0)$ and $M(B_s^0)$. The backgrounds are divided into three different categories. The major background is the combinatorial background, which is coming from the two semi-leptonic B decays, or one semi-leptonic B decay and one misidentified hadron. The second background is the rare peaking background composed of two opposite charge hadrons coming from the same B meson decays (e.g.,: $B \to \pi\pi$, KK), and the final background is the rare semi-leptonic background events coming from three body decay, such as $B \to K(\pi)\mu\mu$. The combinatorial background is estimated using sideband data, whereas Monte-Carlo simulation is used to study the peaking and semi-leptonic backgrounds.

To achieve a good muon identification and reduce hadronic misidentification, Boosted Decision Trees (BDT) are trained using tracking and muon related information from different detector subsystems. Then, the combinatorial backgrounds are suppressed by training a BDT using many discriminant kinematic variables as input. The most powerful discriminating variables are isolation variables, such as muon and B meson isolation, the angle between primary and secondary vertex directions, transverse momentum of B meson, and well reconstructed secondary vertices. The analysis procedure are validated and calibrated using $B^+ \to J/\psi K^+$ and $B_s^0 \to J/\psi\phi$ decays. The analysis is performed in fourteen categories to evaluate the branching fraction, and in eight categories to measure the effective lifetime, depending upon the largest significance and smallest lifetime error, respectively.

The branching fractions are determined with respect to the normalized channel $\mathrm{B}^+ \to J/\psi\mathrm{K}^+$ using the following formula:

$$\mathscr{B}(\mathrm{B}^0_{(\mathrm{s})} \to \mu^+\mu^-) = \frac{n_{\mathrm{B}^0_{(\mathrm{s})}}}{n^{\mathrm{obs}}_{\mathrm{B}^+}} \frac{A_{\mathrm{B}^+}.\epsilon_{\mathrm{B}^+}}{A_{\mathrm{B}^0_{(\mathrm{s})}}\ \epsilon_{\mathrm{B}^0_{(\mathrm{s})}}} \frac{f_{\mathrm{u}}}{f_{\mathrm{s(d)}}} \mathscr{B}(\mathrm{B}^+ \to J/\psi\mathrm{K}^+) \tag{2}$$

for the $\mathrm{B}^0_{(\mathrm{s})} \to \mu^+\mu^-$ channel. Here, $n_{\mathrm{B}^0_{(\mathrm{s})}}$ and $n^{\mathrm{obs}}_{\mathrm{B}^+}$ are the numbers of reconstructed yields of signal and normalization $\mathrm{B}^+ \to J/\psi\mathrm{K}^+$ decays, respectively. $A_{\mathrm{B}^+}.\epsilon_{\mathrm{B}^+}$ and $A_{\mathrm{B}^0_{(\mathrm{s})}}.\epsilon_{\mathrm{B}^0_{(\mathrm{s})}}$ are the acceptance times the selection and reconstruction efficiency for $\mathrm{B}^+ \to J/\psi\mathrm{K}^+$ and $\mathrm{B}^0_{(\mathrm{s})} \to \mu^+\mu^-$; the ratio, $\frac{f_{\mathrm{u}}}{f_{\mathrm{s}}}$, accounts for the b-quark fragmentation fraction into B^+ and $\mathrm{B}^0_{\mathrm{s}}$ mesons. The fragmentation fraction ratio is an external parameter to this measurements, and the value is taken from PDG [7], which is an average of LHCb [8] and ATLAS [9] 7 TeV measurement with an additional uncertainty estimated from the LHCb [10] 13 TeV result:

$$\frac{f_{\mathrm{s}}}{f_{\mathrm{u}}} = 0.252 \pm 0.012(\mathrm{PDG}) \pm 0.015(\text{energy and } \mathrm{p_T} \text{ dependence}) \tag{3}$$

1.2 Results

A three-dimensional unbinned maximum likelihood (UML) fit to the dimuon invariant mass $m_{\mu\mu}$, the relative mass resolution $\sigma(m_{\mu\mu})/m_{\mu\mu}$, and a dimuon bending configuration (either bending towards or away from each other) is performed to determine both the branching fraction. The probability density function used for the UML fit are: a Crystal-Ball function for signal $\mathrm{B}^0_{\mathrm{s}} \to \mu^+\mu^-$ and $\mathrm{B}^0 \to \mu^+\mu^-$ where the width is scaled according to $\sigma(m_{\mu\mu})$; a Gaussian plus Crystal-Ball function for the peaking background; a non-parametric kernel density estimator model for the semi-leptonic background; a first-order Bernstein polynomial for the combinatorial background. The fitted branching fractions are

$$\mathscr{B}(\mathrm{B}^0_{\mathrm{s}} \to \mu^+\mu^-) = [2.9{\pm}0.7(\mathrm{exp}) \pm 0.2(f_{\mathrm{s}}/f_{\mathrm{u}})] \times 10^{-9} \tag{4}$$

$$\mathscr{B}(\mathrm{B}^0 \to \mu^+\mu^-) = (0.8^{+1.4}_{-1.3}) \times 10^{-10} \tag{5}$$

The observed (expected) significance, derived based on Wilk's theorem, for $\mathrm{B}^0_{\mathrm{s}}$ and B^0 decays are 5.6 σ and 0.6 σ (6.5 σ and 0.8 σ), respectively. The fits to the dimuon invariant mass distributions along with likelihood contours are shown in Fig. 1. The observed results are consistent within the uncertainties with the Standard Model predictions and the CMS measurements with the data of the first LHC operation period (Run 1). Since, no excess of a $\mathrm{B}^0 \to \mu^+\mu^-$ signal is observed, a one-sided upper limit of the branching fraction has been estimated using the CLs method. The result is $\mathscr{B}(\mathrm{B}^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10} (3.1 \times 10^{-10})$ at 95 (90%) confidence level (CL).

The measurement of the effective lifetime of the $\mathrm{B}^0_{\mathrm{s}}$ meson is carried out with two methods. The primary method involves the two-dimensional likelihood fit to the invariant mass and to the decay time. The second method is based on a 1D binned likelihood fit approach to the signal only decay time distribution, which extracted using sPlot technique. The fit model used in the primary method involves per event decay time uncertainty as a conditional parameter in the resolution model, and the efficiency as a function of decay time is corrected to the signal shape. The weights used in the

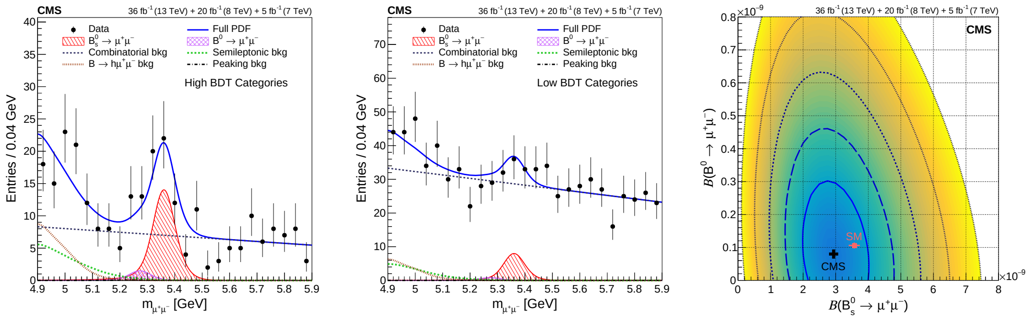

Figure 1: Dimuon invariant mass distributions with fit projection overlays for the branching fraction results where the merged results from the high-(low-)range analysis BDT categories are shown in the left(middle) plot. The final fit results are indicated by continuous lines. The hatched histogram, and the broken lines correspond to the signal component and the different background components, respectively. The right plot shows the likelihood contours for the fit to the branching fractions together with the best-fit value (cross) and the SM expectation (solid square). Details of the analysis are documented in Ref [3].

sPlot method are derived from the branching fraction fit. The effective lifetime is extracted with a modified exponential function which includes resolution and efficiency effects, and a customised algorithm is used to measure the proper asymmetric uncertainties of the effective lifetime. The results are in agreement with each other as well as the SM expectation.

$$\tau_{\mu\mu}(\text{2D fit}) = 1.70\,^{+0.61}_{-0.44}\ \text{ps, and } \tau_{\mu\mu}(\text{sPlot fit}) = 1.55\,^{+0.52}_{-0.33}\ \text{ps} \tag{6}$$

The total uncertainties are dominated by statistical uncertainties compared to the systematic uncertainties.

1.3 ATLAS, CMS and LHCb combined analysis result

A combination [11] of results has been performed by the ATLAS, CMS, and LHCb experiments using a binned two-dimensional likelihood obtained from the fit to dimuon invariant mass distributions. Each likelihood is fitted with analytic function in $\mathscr{B}(\mathrm{B_s^0} \to \mu^+\mu^-) - \mathscr{B}(\mathrm{B^0} \to \mu^+\mu^-)$ plane where both branching fractions are constrained to be positive. A variable-width Gaussian is used to account for the likelihood asymmetry. This function also considers the correlation between the two observables because of overlap of two mass peaks from the dimuon mass resolution. Then the sum of three binned log-likelihoods is fitted using a two dimensional variable-width Gaussian and the central value and uncertainties of the branching fractions are evaluated from the maximum. The resulting branching fractions are

$$\mathscr{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9} \tag{7}$$

$$\mathscr{B}(\mathrm{B^0} \to \mu^+\mu^-) = (0.6 \pm 0.7) \times 10^{-10} \tag{8}$$

No $\mathrm{B^0} \to \mu^+\mu^-$ signal decay has been observed, and an upper limit is calculated using the one-dimensional negative log-likelihood. The result is $\mathscr{B}(\mathrm{B^0} \to \mu^+\mu^-) < 1.6 \times 10^{-10} (1.9 \times 10^{-10})$ at 95% (90%) CL. The results are compatible with the SM at 2.4 σ for $\mathrm{B_s^0} \to \mu^+\mu^-$ and 0.6 σ

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for $B^0 \rightarrow \mu^+\mu^-$ while the two-dimensional compatibility is 2.1 σ. Similarly, the upper limit for the ratio of the branching fractions is $\mathcal{R} < 0.052$ (0.060) at 90 (95)% CL. The effective lifetime is also measured by the CMS and LHCb experiments. The combined measurement is evaluated to be $\tau_{\mu\mu} = 1.91\,^{+0.37}_{-0.35}$ ps [11].

2. Search for $\tau \rightarrow 3\mu$ decays at CMS

The lepton flavour violating, $\tau \rightarrow 3\mu$ decay, does not produce a neutrino in the final state. It is allowed in the SM by neutrino oscillation, which results in small and not experimentally measurable branching fractions. The decay is sensitive to beyond standard model physics contributions, and the decay rate can be enhanced. Various experiments have performed this search because the three muons final state is experimentally reachable and clean. No sign of the signal has been observed yet; the best limit, $\mathscr{B} < 2.1 \times 10^{-8}$ at 90% CL, comes from the Belle experiment [12]. CMS performed a search for the $\tau \rightarrow 3\mu$ decay by using two separate decay channels, τ leptons produced in D and B hadron decays, and the W boson decay, using the 33 fb^{-1} data collected at 13 TeV in the year 2016 [13]. The events are triggered with two muons plus a track with different p_T criteria, having a common vertex, and the invariant mass should be in the range 1.60 – 2.02 GeV. The combination of three-muon charge at the offline stage in the event are required to be ± 1. For the W boson analysis, the background arising from the hadronic resonances is vetoed. The analysis object is the three isolated muon jets with a large missing energy. Background suppression is achieved by training a BDT using events from sideband data and signal MC. The most discriminating variables are the τ candidate relative isolation, transverse W mass, and $p_T^{3\mu}$. The data sample is divided into two categories based on the τ pseudo-rapidity because of the difference in the τ invariant mass resolution. Another independent search analysis for the τ decay is performed using the heavy flavour(HF) decay (where both D_s, and the B hadron decay to signal τ leptons). The normalization channel $D_s^+ \rightarrow \phi\pi^+ \rightarrow \mu^+\mu^-\pi^+$ is selected with the same trigger requirement and same selection criteria. The D_s mesons can be produced directly in the pp interaction and in B-hadron decays or from the B-meson decay. The fraction of non-prompt D_s events is evaluated from a binned template fit to the proper decay length distribution. Details can be found in Ref. [13].

The events are categorized in two ways; first, the three-μ mass resolution is computed event-by-event ranging from 0.4% to 1.5%, depending upon the candidate's rapidity and then according to mass resolution, events are split into three categories. BDT are trained in each category using vertex quality and muon quality variables to distinguish signal candidates from backgrounds. Each BDT output is separated into three categories depending upon the signal to background ratio. The lowest ratio range is dropped, resulting in six categories in total.

A simultaneous maximum likelihood fit to the three-muon invariant mass is performed in the two categories of the W boson analysis (as shown in Fig. 2) and six categories of the heavy flavour analysis (as shown in Fig. 3) to extract the branching fraction $\mathscr{B}(\tau \rightarrow 3\mu)$. For the W boson analysis, a Gaussian function with fixed mean and width is used to model the signal invariant mass shape (Fig. 2). For the heavy-flavour analysis, a Gaussian plus Crystal-Ball function with fixed mean and width defines the signal shape. For both analyses, the shapes are obtained from the fit to respected simulated samples in a different category. In all the cases, the background is modelled with an exponential function with parameters and normalization determined by the fit. As can be seen, no evidence of a signal is found, and the observed (expected) upper limit is calculated using the CLs method. The observed (expected) upper limit at 90% CL on $\mathscr{B}(\tau \to 3\mu)$ using all events is $8.0 \times 10^{-8}(6.9 \times 10^{-8})$.

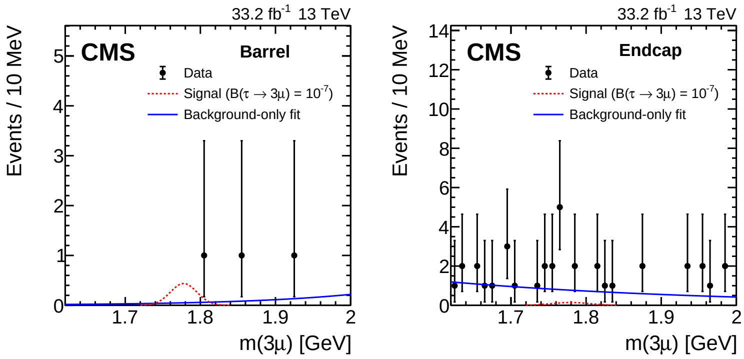

Figure 2: Trimuon invariant mass distributions for barrel (left) and endcap (right) categories of the W boson analysis. The data are shown with filled circles and vertical bars representing the statistical uncertainty. The background-only fit and the expected signal for $\mathscr{B}(\tau \to 3\mu) = 10^{-7}$ are shown with solid and dashed lines, respectively.

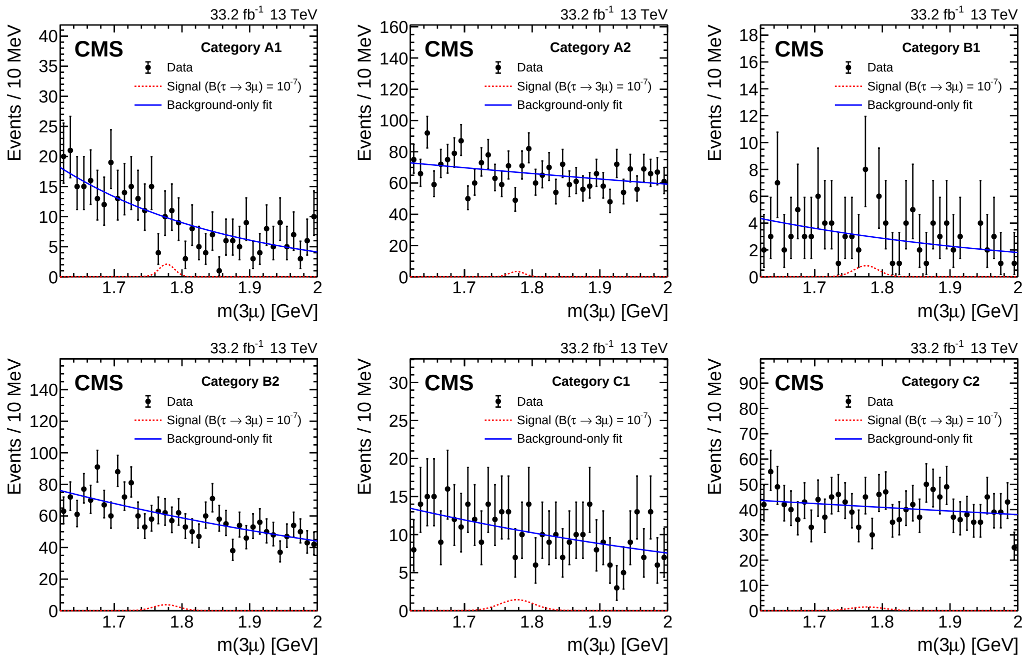

Figure 3: Trimuon invariant mass distributions in the six independent event categories used in the heavy-flavor analysis and defined in the text: A1, A2, B1, B2, C1, C2. The data are shown with filled circles and vertical bars representing the statistical uncertainties. The background-only fit and the expected signal for $\mathscr{B}(\tau \to 3\mu) = 10^{-7}$ are shown with solid and dashed lines, respectively.

The fit has been performed separately on the W boson and heavy-flavor analyses resulting in observed (expected) 90% CL upper limits of 20×10^{-8} (13×10^{-8}) and 9.2×10^{-8} (10.0×10^{-8}), respectively. Systematic uncertainties are integrated in the analysis via nuisance parameters.

3. Summary

In summary, a study of the $\mathrm{B_s^0} \to \mu^+\mu^-$ decay properties and a search for $\mathrm{B^0} \to \mu^+\mu^-$ have been presented based on the pp collision data collected by the CMS experiment at the LHC between 2011 and 2016. The $\mathrm{B_s^0} \to \mu^+\mu^-$ decay is observed with a 5.6 σ significance. The branching fraction and the effective lifetime of the $\mathrm{B_s^0}$ meson in $\mathrm{B_s^0} \to \mu^+\mu^-$ decay are in agreement with the SM predictions. No significant $\mathrm{B^0} \to \mu^+\mu^-$ decay has been observed and the upper limit is set on the branching fraction.

The latest combined analysis using ATLAS, CMS and LHCb results has been discussed as well. The $\mathrm{B_s^0} \to \mu^+\mu^-$ branching fraction and the effective lifetime are measured and are in agreement with SM predictions and the different experiments. An upper limit on the ratio of the $\mathrm{B^0} \to \mu^+\mu^-$ and $\mathrm{B_s^0} \to \mu^+\mu^-$ branching fraction is evaluated to be $\mathcal{R} < 0.052$ (0.060) at 90 (95)% CL.

The search for the lepton-flavor violating $\tau \to 3\mu$ decay has been performed using CMS data collected in 2016, corresponding to an integrated luminosity of 33 $\mathrm{fb^{-1}}$. The analysis uses the τ leptons produced from D and B meson decays. No hint of a signal is observed, and the upper limit on the branching fraction is set to 8.0×10^{-8} (at 90 % CL).

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